# *Air Traffic Management Technology Demonstration – 1 (ATD-1)*

## Controller Managed Spacing Tool Advisory Algorithm

**ATD1-CMSAlg-201309 Rev -**

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**Revision History**

| **Rev** | **Date** | **Sections Affected** | **Description of Change** | **Author** |
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# 1 Introduction

This document provides an overview of the Controller Managed Spacing (CMS) tool and the algorithms supporting its function as implemented within the operational Traffic Management Advisor (TMA). The CMS tool is an advisory tool that aids air traffic controllers to meet precision scheduled times of arrival (STAs). The current version of the CMS tool was developed by Airspace Operations Laboratory (AOL) researchers at NASA Ames Research Center. The remainder of this document is organized to fulfill the objectives of providing the reader with an understanding of the following three topics: the motivation for the CMS concept, the intended use of the CMS tool within the TMA, and the underlying algorithms supporting the CMS tool advisories.

# 2 Background: Final Approach Spacing Aids Research and Development

As previously mentioned, the CMS tool is an advisory tool intended to aid air traffic controllers to meet precise metering times in the TRACON. The original CMS tool provided air traffic controllers with two forms of advisories to accomplish this objective: slot markers and speed advisories. Efforts to provide automated assistance to air traffic controllers for spacing of arrival aircraft date to at least the 1960s (Holland, MITRE Report M70-9 Rev. 2, Mar 1974). Today's CMS tool leverages the findings of NASA research dating to the 1980s. Credeur, et al., investigated a variety of advisory aid formats for reducing inter-arrival spacing variance for two arrival procedures (NASA TP 3399, December 1993). During this time, NASA was also developing the Traffic Management Advisor (TMA) and the Final Approach Spacing Tool (FAST), the latter aimed at assisting TRACON air traffic controllers with sequencing and spacing arriving aircraft at highly congested airports. A brief review of these efforts and their key findings are provided in the following paragraphs as context for the development of the eventual CMS advisory format.

Credeur assessed the performance and utility of three air traffic controller decision support aid formats: centerline slot marker, DIrect Course Error (DICE) countdown, and graphic marker. Each of these display aids was used in some form within the decision support tools being developed at the time in cooperation with the Federal Aviation Administration (FAA): the Converging Runway Display Aid (CRDA), the Descent Advisor (DA), the Traffic Management Advisor (TMA) and the Final Approach Spacing Tool (FAST).The centerline slot marker was a (~0.75 nm diameter) circle displayed on the extended runway centerline that progressed along the extended runway centerline until reaching the Final Approach Fix (FAF) at the assigned STA. Controllers were to vector aircraft and issue speed instructions to aircraft in an attempt to merge each aircraft with its centerline slot marker prior to the FAF and to maintain position coincident with the marker until the FAF; no automated guidance was given to controllers for how they should control the aircraft to merge with the slot marker and achieve proper spacing. Of note, the rate of slot marker progress was determined a priori (equivalent to 170 KIAS @ 7,200 ft MSL altitude) and the centerline slot markers were not coincident with the aircraft route, except once an aircraft had joined the localizer. The DICE countdown advisory format presented the controllers with speed and heading (turn) guidance in the form of textual advisories in each aircraft's full data block (FDB). A countdown timer was also textually displayed in the FDB to assist the controller in precise timing of the execution of the advised turns and speed instructions such that aircraft arrived at the FAF at their assigned STA. Lastly, the graphic marker format displayed advised turns and speeds with graphical markers indicating where an advised turn or speed instruction should be issued. In simple terms, the DICE countdown provided a textual description of the advised turns and speeds with an indication of WHEN they should be executed, whereas the graphic advisories provided a pictorial representation of WHERE they should be executed. Analysis of human-in-the-loop simulation results led to a number of important findings for development of effective decision support for TRACON air traffic controllers. First, all three advisory formats showed improved spacing performance (although the centerline slot marker failed to show improvement in one simulation condition). The graphic marker and DICE formats were found to be superior to the centerline slot marker across all simulation conditions, having both reduced inter-arrival spacing variance and lower reported controller workload. The centerline slot marker format had significantly increased controller workload reported compared to the baseline condition without automated spacing aids. Comparing the DICE and graphic markers, the DICE format showed the greatest reduction in inter-arrival spacing variance, while the graphic marker had the lowest reported controller workload (both DICE and graphic marker format were less than reported for the baseline, no display aid, condition). These findings, coupled with simulations being conducted with the FAST led to a phased approach to development of the FAST for operational testing and implementation.

The Final Approach Spacing Tool, as initially conceptualized, employed graphical and FDB advisories to assist the controller in precisely guiding aircraft along conflict-free trajectories to minimize excess inter-arrival spacing. However, generation of acceptable graphic marker advisories in the dynamic environment of a congested TRACON proved highly difficult. Furthermore, controller feedback following FAST simulations indicated a preference for simple FDB advisories within the context of terminal operations at that time (late 1980s-mid 1990s). FAST development was branched into two, largely independent, decision support tools: passive FAST (pFAST) and active FAST (aFAST). The latter retained the graphic marker aids including turn advisories, and the former was greatly simplified to include advisories only for arrival runway and sequence number of arrival on assigned runway. As such, pFAST presented TRACON controllers with an efficient plan, but left the method of execution to be determined by the controller; controllers were uncomfortable with issuing control instructions exactly as advised by aFAST while retaining full responsibility for separation of aircraft according to FAA Order 7110.65. pFAST was developed through thousands of hours of HITL simulation and eventually tested operationally at the Dallas Fort-Worth TRACON (D10). Operational field trials proved largely successful, showing significant airport throughput improvements and benefitting both arrival and departure aircraft. While the nationwide deployment effort for pFAST stalled and was eventually abandoned, a number of vital lessons were learned that would be applied to future decision support aids for terminal airspace. First, it was clear that the benefits hypothesized by decades of research could be realized in a highly congested operational environment, even with a reduced, simple set of advisories. Second, the apparent conflict of controller separation responsibility with the advisory compliance necessary to achieve automation benefits would likely hinder implementation of automation wherever that automation is perceived to limit the controller's ability to fulfill their primary responsibility (safe separation of aircraft). The following section describes how CMS employs adapted DICE/FAST-style speed advisories and essentially reinvented slot markers in the context of modern air traffic operations to overcome the obstacles that have hindered prior efforts.

# 3 CMS-TMA Integration and Concept of Use

The CMS tool was designed to operate in concert with an air traffic scheduler providing the STAs required as inputs to the CMS algorithms and was originally implemented in the AOL's Multi-Aircraft Control System (MACS). The CMS tool has since been incorporated within the TMA tool to provide controllers with an integrated solution to precisely meter arriving aircraft into the terminal airspace and to achieve minimal excess spacing on final approach. The TMA tool computes STAs for each metered aircraft at each metering location based on aircraft trajectory predictions and satisfying all operational constraints (e.g. separation minima, arrival rate restrictions). The STAs are depicted on timelines on controller displays. The CMS tool uses these STAs to compute reference (or slot marker) trajectories that comply with the TMA STAs and provide a feasible speed profile for each aircraft. From this reference trajectory, the CMS tool generates two types of advisories: slot markers and speed advisories. The slot markers provided by the CMS tool are distinctly different from the centerline slot markers previously assessed in two important ways: 1) CMS slot markers are based on trajectory predictions instead of a static approximation of final approach speed, and 2) the CMS slot markers progress along the entire arrival path of the aircraft and not only along the extended runway heading of the final approach. These two distinctions allow CMS slot markers to be used more strategically than the prior centerline slot markers, allowing for greater use of speed adjustments to affect inter-arrival spacing: a requirement for effective use of RNAV and RNP terminal procedures. The speed advisories presented by CMS are similar to those evaluated previously by Credeur and in aFAST studies. In contrast, however, the CMS speed advisories are not expected to be followed precisely: controllers are given a broader objective in concert with targets presented by the CMS slot markers. In this sense, a CMS speed advisory can be viewed more as continuous feedback to the controller performing the tasks of spacing and separating aircraft than as an instruction to issue a speed clearance to an aircraft at a specified time or location.

The CMS tool is designed to run in the TMA while the aircraft is in en route as well as in terminal airspace, with the reference trajectory being generated once the aircraft's schedule is frozen, both to the meter fix and along its route in terminal airspace. However, the display of the CMS slot marker is usually suppressed until the aircraft is in terminal airspace. The speed advisory is generated for every aircraft in the TRACON at every track update.

The slot marker advisory for a flight consists of a marker that moves along a designated four-dimensional (4D) trajectory that TMA has adapted and computed for this flight. This "reference trajectory" meets the STAs to all the terminal meter points generated by TMA for this flight. Currently, the scope of the terminal meter points is all of the meter points from the meter fix to the runway threshold. At any given point in time between a flight's meter fix and runway threshold STAs, a corresponding slot marker position and airspeed advisory are generated from the reference trajectory and presented to the air traffic controller. The slot marker's position and airspeed is a reference state indicator of a state that flight can be in to meet the downstream meter points' STAs.

The speed advisory for a flight consists of an airspeed and a target waypoint. The airspeed in the advisory is intended to be issued to the flight by the air traffic controller. A target waypoint is the next meter point at which the CMS speed advisory algorithm predicts the flight can meet the schedule point's STA by speed control only. There could be a series of speed advisories shown at different times for the same target waypoint. If a speed advisory is not feasible for the next meter point, then the algorithm will try to meet downstream schedule waypoints in sequence until a feasible advisory is found. It's possible, given the path that the flight is on, as well as its current position and speed, that there is not a feasible speed solution to meet any downstream meter points. In such a case, a speed advisory and its associated target meter point will not be issued.

# 4 Goals of Controller Managed Spacing Tool (CMS) Advisory Algorithm

The first task of the CMS algorithm is to generate a reference trajectory for each scheduled flight that meets the scheduled time-of-arrival at each meter point. It does this in part by choosing a set of speeds that fall between the slow and the fast speed restrictions from the predefined profile. This reference trajectory is currently used to extract the slot marker position and speed at a given time.

The next task is to compute a feasible target speed advisory and a meter point such that the flight is capable of arriving at the scheduled waypoint on time and can thereafter capture and fly the slot marker speed.

# 5 Input

1. Track data used to generate 4D trajectories (e.g., position of aircraft, CAS, heading, altitude, etc.)
2. Altitude, speeds (fast, nominal, and slow), and path distance for each meter point from the meter fix to the runway, inclusive.
3. Scheduled times-of-arrival generated by TMA's scheduler (Dynamic Planner) at each meter point.

# 6 Output

1. Reference trajectory for each scheduled flight.
2. Speed advisories for each scheduled flight, consisting of a speed and a meter point.

# 7 Bisection Approach

Definition of 'bisection method' from Wikipedia : The **bisection method** in mathematics is a root-finding method which repeatedly bisects an interval and then selects a subinterval in which a root must lie for further processing.

To compute reference trajectories and speed advisories, the algorithm needs a simple but efficient method to determine an optimal speed from a given speed range for each speed restriction point. It must do this in real-time after each track update, so algorithm speed is crucial. The CMS algorithm uses a bisection approach which initially starts with a given speed range and keeps reducing the speed range by bisecting it and discarding one of side of the slice.  To determine which section will be discarded, the algorithm compares the ETA and the STA at the target meter point from the returned 4D trajectory. Once the section is determined, the speed used to generate the trajectory becomes either the upper or lower boundary of a new speed range, depending on which section is discarded. This procedure is repeated until the algorithm finds a speed that meets the STA, or until the speed range is too small to continue.

# 8 Tolerance

To determine whether or not an obtained speed profile is acceptable, the algorithm generates a 4D trajectory with the speed profile, and compares the STA and the ETA from the returned trajectory at each meter point. When it compares two times, the algorithm uses 5 seconds of tolerance by default. For example, if the STA at a meter point is 10:05:00 (hh:mm:ss), any ETA between 10:04:55 and 10:05:05 is considered acceptable.

# 9 Generation of reference trajectory

The reference trajectory is generated whenever a flight's schedule is frozen or rescheduled while it's frozen, so that frozen STAs at meter points are available. The generated trajectory starts at the position (typically Center freeze horizon) at the time it gets frozen and ends at the assigned runway.

To compute speeds to meet STAs, the algorithm iterates through all meter points backward from the runway up to the meter fix, and finds a speed within the predefined range at each speed restriction point by applying the bisection approach described above.

The reason for using backward iteration instead of forward iteration is that the speed change at one speed restriction waypoint not only affects the flying time to the next downstream waypoint, but also affects flying time from one upstream waypoint to the speed restriction waypoint as well.

Since the runway speed restriction is fixed and not changeable, the algorithm starts the process with the last waypoint before the runway.

Although the algorithm iterates backward through each meter point, if there are any additional speed restriction points between two meter points, the algorithm iterates forward through those intermediate restriction points to compute the speeds until the STA of the target meter point is met. One potential problem of the forward iteration over restriction points is that the speed at one restriction point could be lower than one at the downstream restriction point. To avoid such undesirable speed increases, the algorithm also makes sure that speeds at downstream restriction points are not greater than the speed that is being iterated on.

Figure 1 shows the flowchart for the slot marker algorithm. The following describes variables and constants used in the flowchart.

| | | |
|---|---|---|
| MP | : | meter point at which the algorithm is trying to meet the STA |
| SRP | : | speed restriction waypoint selected to adjust speed |
| SPEED | : | speed at selected speed restriction waypoint used to generate 4D trajectory |
| UP | : | upper boundary of speed which the algorithm keeps track of |
| LO | : | lower boundary of speed which the algorithm keeps track of |
| FAST | : | fast speed from the speed profile at the selected speed restriction waypoint |

| | | |
|---|---|---|
| SLOW | : | slow speed from the speed profile at the selected speed restriction waypoint |
| MP_ETA | : | ETA at a selected meter point |
| RWY_ETA | : | ETA at runway from generated trajectory |
| RWY_STA | : | STA at runway from the scheduler |
| MF | : | meter fix |
| RWY | : | runway |

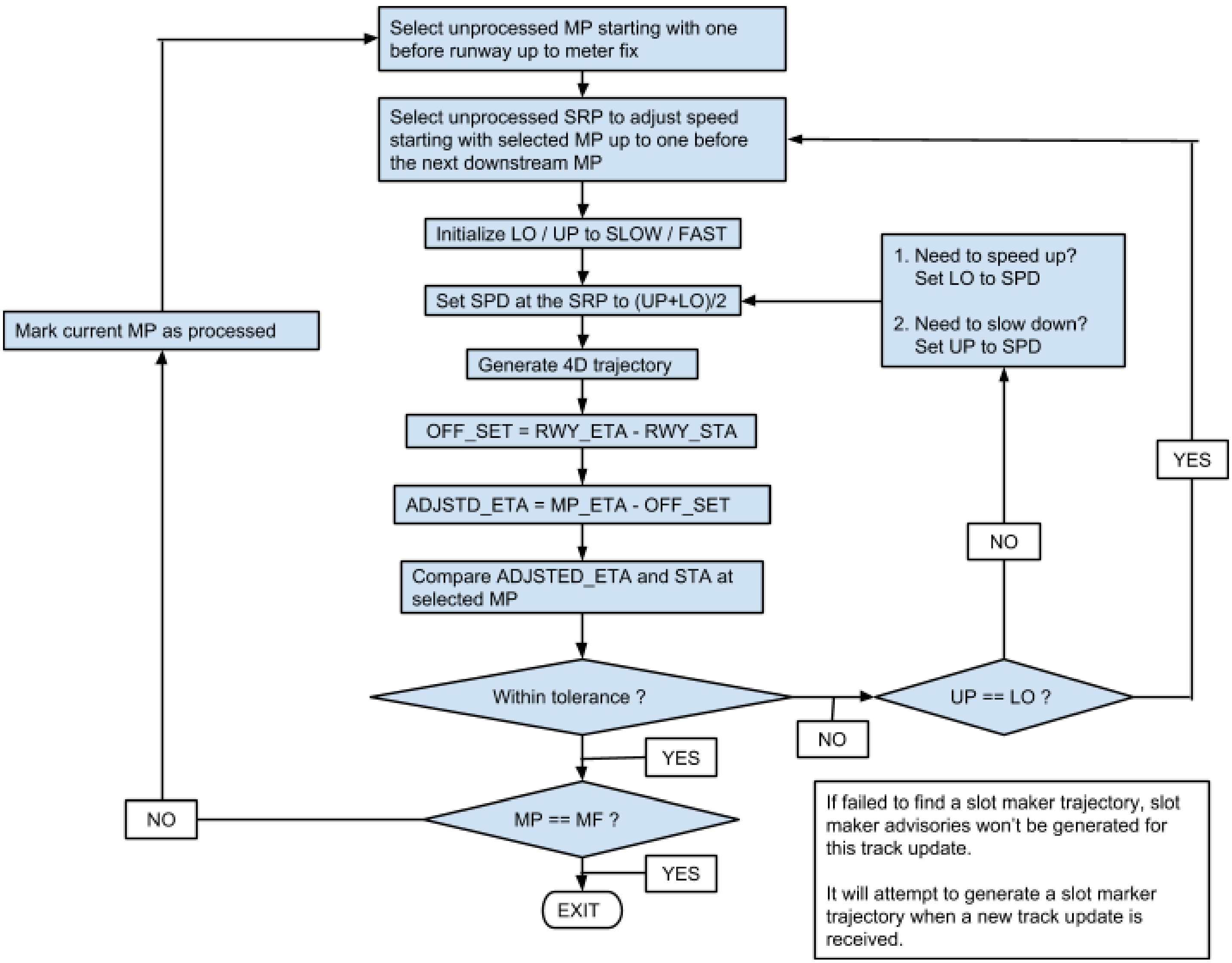


Figure 1. Slot Marker Algorithm Flow Chart

# 10 Computation of Speed Advisories

The speed advisories are generated for the frozen flights whenever a new TRACON track update is received. The algorithm generates 4D trajectories from each flight's current position to the assigned runway, and finds a speed and the earliest downstream meter point that the aircraft can arrive at the scheduled time if the speed is captured by applying the bisection approach described above.

While the slot marker algorithm iterates backward, the speed advisory algorithm iterates forward through the meter points from the current position toward the runway. First, the algorithm starts with the previous speed advisory trajectory, if available, otherwise, the reference trajectory, and then it finds a speed and the target meter point by applying the bisection approach described above.

For additional speed restriction points between two meter points, the speed advisory algorithm adjusts speeds at all restriction points together, while the slot maker algorithm adjusts the speeds one restriction point at a time. Since all speeds between two meter points are uniformly adjusted to the middle values in the ranges, the time difference gets distributed over the multiple restriction points.

Even though a bisection algorithm is sequential and supposed to give the best output at the end of the algorithm, in the speed advisory algorithm, the last iteration is not necessarily the best because of a trajectory modeler limitation that it doesn't capture the requested speed if the distance to the next downstream point is not long enough. To resolve the issue, the algorithm stores all speed advisories that give an ETA within the tolerance, and selects the best one among the stored advisories at the end of the algorithm. To determine the best one, the algorithm simply compares the STA and the ETA at the target meter point and picks the one that gives the least difference.

Figure 2 shows the flowchart of the speed advisory algorithm. The following describes variables and constants used in the flowchart.

| | | |
|---|---|---|
| MP | : | meter point at which the algorithm is trying to meet the STA |
| SRP | : | speed restriction waypoint selected to adjust speed |
| SPEED | : | speed at selected speed restriction waypoint used to generate 4D trajectory |
| UP | : | upper boundary of speed which the algorithm keeps track of |
| LO | : | lower boundary of speed which the algorithm keeps track of |
| FAST | : | fast speed from the speed profile at the selected speed restriction waypoint |
| SLOW | : | slow speed from the speed profile at the selected speed restriction waypoint |
| MP_ETA | : | ETA at a selected meter point |
| RWY_ETA | : | ETA at runway from generated trajectory |
| RWY_STA | : | STA at runway from the scheduler |
| MF | : | meter fix |
| RWY | : | runway |

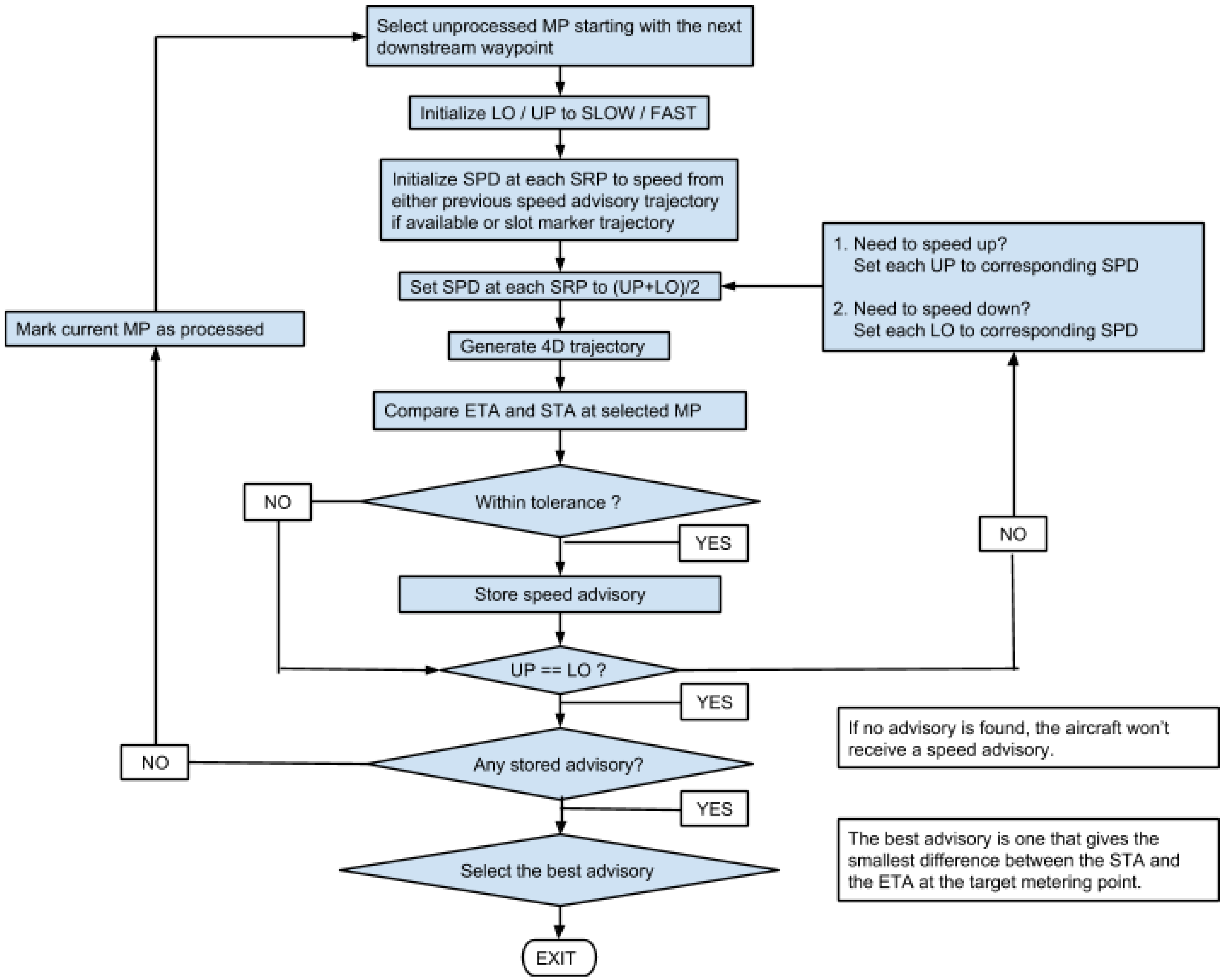


Figure 2. Speed Advisory Algorithm Flow Chart

Title of Package:(*edit*)
**ATD-1 TMA DOCUMENTS FOR APPROVAL (NINE DOCUMENTS)**
Routernumber:21936

Group this package under:
**HQ_ARMD_ASP**

Routing Package Administrator:Angela Boyle(*edit*)
Comments:(*edit*)

****URGENT REQUEST TO COMPLETE APPROVAL PROCESS FOR THE TMA DOCUMENTS PRIOR TO FRIDAY MORNING, SEPTEMBER 27, 2013****

Nine items enclosed:
1. ATD-1 Scheduling Algorithm Overview Version 2.0 (HSwenson & LChen, September 2013) / 7.01 ATD1-TMAlgDescription-20130913-V2.0.pdf

2. Controller Managed Spacing Tool Advisory Algorithm (CLee & LChen, September 2013) / 7.02 ATD1-CMSAlg-201309-Rev-.pdf

3. Overview of TMA RNP Route Processing (SChan, September 2013) / 7.03 ATD1-RNPRouteProcessing-201309-Rev-.pdf

4. Overview of RTMA Trajectory Synthesis Changes (SChan, September 2013) / 7.04 ATD1-TSSoftwareChanges-201309-Rev-.pdf

5. Overview of RTMA Dynamic Planner Changes (LChen, September 2013) / 7.05 ATD1-RTMADynPlannerChanges-201309-Rev-.pdf

6. STARS-RTMA Functional Description (Cisek, September 2013) / 7.06 ATD1-STARS-RTMAFuncDesc-201309-Rev-.pdf

7. Required Navigation Performance (RNP) Radius Fix (RF) Leg Implementation for Aero Tech Demo 1 (ATD-1) (ALee, et al) / 7.07 ATD-1 RNP RF Leg Changes-20120316-Rev7.pdf

8. Staggered Parallel Approaches Algorithm in TMA (LChen, September 2013) / 7.08 ATD1-StaggerAlgorithmTMA-201309-Rev-.pdf

9. RTMA Source Code Change Analysis (Eshow, Sep 2013) / 7.09 ATD1-SourceCodeAnalysis-201309-Rev-.pdf

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| 1 | **Mirna Johnson**<br>**Title:**Systems Engineer<br>mirna.g.johnson@nasa.gov<br>**Phone:**650.604.1026<br>**Comment From Reviewer:**<br><br>9/26/2013 4:11:51 PM<br>**Response To Reviewer Comments:**<br>(Add/Edit)<br>Email Sent | Yes-<br>9/26/2013<br>4:11:51 PM | | | | |
| | CC-P \| **David Squires**<br>**Title:**Systems Engineer<br>david.d.squires@nasa.gov<br>**Phone:**209.479.3082<br>**Comment From Reviewer:**<br><br>**Response To Reviewer Comments:**<br>(Edit)<br>Email Sent | CC<br>Reviewer- | | | | |
| 2 | **Ronald Johnson**<br>**Title:**IET-ATD-1 Technical Lead<br>ronald.d.johnson@nasa.gov<br>**Phone:**650.604.6699<br>**Comment From Reviewer:**<br><br>9/26/2013 4:14:42 PM<br>**Response To Reviewer Comments:**<br>(Add/Edit)<br>Email Sent | Yes-<br>9/26/2013<br>4:14:42 PM | | | | |
| 3 | **John Robinson**<br>**Title:**ATD-1 Chief Engineer<br>john.e.robinson@nasa.gov<br>**Phone:**650.604.0873<br>**Comment From Reviewer:**<br>All of the documents with Rev #"s should have Rev 1.0 assigned. There seems to be 7 such documents in the package.<br>9/26/2013 4:43:22 PM<br>**Response To Reviewer Comments:**<br>(Add/Edit)<br>Email Sent | Yes-<br>9/26/2013<br>4:43:21 PM | | | | |
| | **William Johnson**<br>**Title:**ATD-1 Deputy Chief Engineer | | | | | |

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| 3 | | william.johnson@nasa.gov<br>**Phone:**757.864.3858<br>**Comment From Reviewer:**<br><br>9/26/2013 5:02:30 PM<br>**Response To Reviewer Comments:**<br>(Add/Edit)<br>Email Sent | Yes-<br>9/26/2013<br>5:02:30 PM | | | | | | |
| 4 | | **Leighton Quon**<br>**Title:**SAIE Project Manager<br>leighton.quon@nasa.gov<br>**Phone:**650.604.3073<br>**Comment From Reviewer:**<br><br>9/26/2013 9:21:39 PM<br>**Response To Reviewer Comments:**<br>(Add/Edit)<br>Email Sent | Yes-<br>9/26/2013<br>9:21:39 PM | | | | | | |
| | CC-P | **Mike Madson**<br>**Title:**Ast, Engineer Project Management<br>mike.madson@nasa.gov<br>**Phone:**650.604.3621<br>**Comment From Reviewer:**<br><br>**Response To Reviewer Comments:**<br>(Edit)<br>Email Sent | CC<br>Reviewer- | | | | | | |
| | CC-P | **Easter Wang**<br>**Title:**Project Controls Analyst<br>easter.wang@nasa.gov<br>**Phone:**650.604.3923<br>**Comment From Reviewer:**<br><br>**Response To Reviewer Comments:**<br>(Edit)<br>Email Sent | CC<br>Reviewer- | | | | | | |
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|---|---|---|---|
| 21936_7.01-ATD1-TMAlgDescription-20130913-Rev2.0.pdf | 1. ATD-1-Sched Alg. | Add Revison | |
| 21936_7.02-ATD1-CMSAlg-201309-Rev-.pdf | 2. CMS Alg | Add Revison | |
| 21936_7.03-ATD1-RNPRouteProcessing- | 3. RNP Route Processing | Add | |

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| 201309-Rev-.pdf | 3. RNP Route Processing | Revison | |
| 21936_7.04-ATD1-TSSoftwareChanges-201309-Rev-.pdf | 4. TS Software Changes | Add Revison | |
| 21936_7.05-ATD1-RTMADynPlannerChanges-201309-Rev-.pdf | 5. RTMA Dyn Planner Changes | Add Revison | |
| 21936_7.06-ATD1-STARS-RTMAFuncDesc-201309-Rev-.pdf | 6. STARS RTMA Func. Desc. | Add Revison | |
| 21936_7.07-ATD-1-RNP RF-Leg-Changes-20120316-Rev7.pdf | 7. RNP RF Leg Changes | Add Revison | |
| 21936_7.08-ATD1-StaggerAlgorithmTMA-201309-Rev-.pdf | 8. Stagger Algorithm TMA | Add Revison | |
| 21936_7.09-ATD1-SourceCodeAnalysis-201309-Rev-.pdf | 9. Source Code Analysis | Add Revison | |
| Add File | | | |